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Effects of energy band structure on gallium arsenide based MOSFET

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ABSTRACT

This research work is focused on material science and semiconductor engineering. It emphasized on the semiconductor material such as Gallium arsenide (GaAs). The Gallium arsenide semiconductor material was used as a group III-V compound for metal-oxide semiconductor field effect transistor (MOSFET) modeling. The band-gap energy structures were analyzed by using material parameters such as Varshni parameters, temperature and doping concentrations. Then, an electrical characteristic was carried out depending on the current and voltage relationship. The current flowing in the device is associated with a gate voltage applied to the device. From this paper, the analysis of MOSFET modeling was investigated using mathematical equations and MATLAB simulation.

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1. Introduction

Gallium arsenide (GaAs) is one type of semiconductor material compounds and it has a zinc blende crystal structure. The material Gallium and the material Arsenide are known as group III and V materials in the periodic table of semiconductor engineering. The two materials of gallium and arsenide have the same quantities of the element gallium (Ga) and element arsenic (As), respectively. The structure of gallium arsenide semiconductor material is the result of two equivalent interpenetrating face-centered cubic (FCC) lattices of gallium and arsenide [1]. Fig. 1 shows the crystal structure of GaAs.

Gallium arsenide semiconductor material can be doped to form both n- and p- type materials. Tellurium, selenium, sulfur, which are group-VI elements, are donors to gallium arsenide. Group II elements, for example cadmium, magnesium, zinc, and are known to be acceptors with respect to GaAs material. In gallium arsenide compound, group IV elements such as silicon and carbon are known to be amphoteric dopants [3].

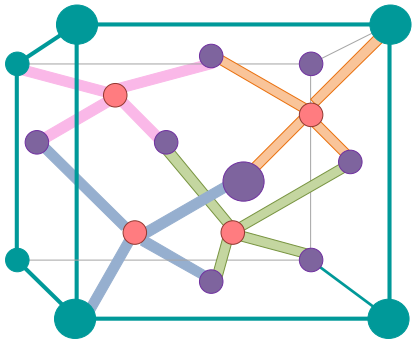

Fig. 1 Crystal structure of GaAs semiconductor material [2]

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Although silicon is known to be a gallium site when the doping concentration level is below 10^{19} cm^{-3}, the silicon is like a donor. As there are two dissimilar atoms in the compound, impurity atoms such as in group II, group IV and group VI can act as low donors and acceptors. Moreover, doping can create GaAs semi-insulating [4].

One of the great advantages of gallium arsenide semiconductor material compound is that the material has semi-insulating properties in some device fabrication technologies. These properties make it a low capacitance substrate; hence, the device can increase its speed [1]. It can also simplify the device isolation, which could be accomplished in some cases. Actually, semi-insulating gallium arsenide could result in a resistivity as high as 10^8 Qcm. Otherwise, the value of resistivity of semi-insulating GaAs is about $10^7\Omega$cm in practical usages. Therefore, there are different techniques of doping and altering the properties of GaAs [5], [6]

MOSFETs (metal-oxide-semiconductor field effect transistors) are offered in enhancement and depletion modes of operation. Moreover, the enhancement and depletion types of MOSFETs are categorized into p-channel and n-channel types of transistor as shown in Fig. 2. The n-channel transistor has n-channel region between source and drain. The gate and source terminals are heavily doped with n-type semiconductor materials [7].

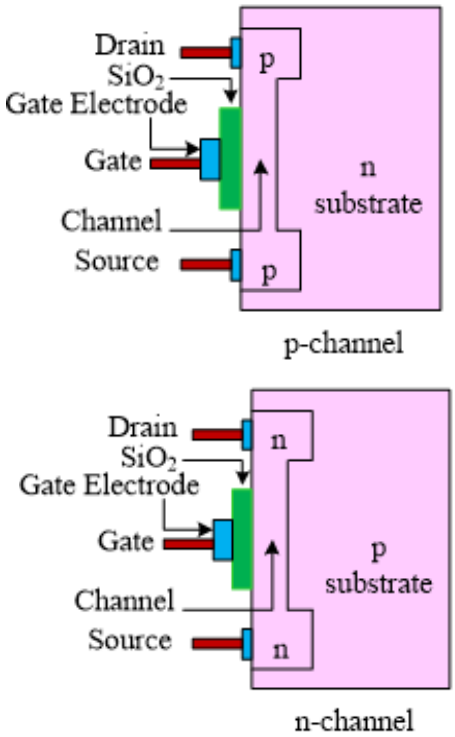

Fig. 2 P-Channel and N-Channel MOSFET [9]

The substrate region is doped with p-type semiconductor material to form p-doped GaAs. The drain current of the device flows between source and drain electrode and this current occurs because of electron flows. The current flowing through the device is controlled by the gate voltage [8].

2. Properties of Gallium Arsenide (GaAs) Material

GaAs is a semiconductor material, which has a zinc blende lattice structure. The lattice structure of this compound is very comparable to the lattice structure of diamond. However, the zinc blende structure differs from the diamond as there are two unique types of atoms in the lattice. In the GaAs, Ga atoms are occupied as four atoms and the rests are occupied as As-atoms. The important characteristics and properties of both structures are that atoms of both structures are linked together to form a tetrahedron [4]. The knowledge on different kinds of crystal structures is very important in determining the distances between neighboring atoms in a crystal. Also, the values of lattice constant are essential to control some of the important properties (physical and electrical) of crystals in a semiconductor [10]. Note that, the distance between two neighboring atoms in a lattice may be less than the lattice constant depending on the crystal structure. Table 1 shows the properties of the gallium arsenide material [4].

The gallium arsenide material also has a covalent bonding with some ionic character. GaAs is utilized in the fabrication (manufacture) of several devices like solar cells, laser diodes, infrared light-emitting diodes, optical windows and monolithic microwave integrated circuits. GaAs can also be utilized as a substrate material at the semiconductor laboratory in performing the epitaxial growth of compounds such as InGaAs and AlGaAs [10], [11]. Besides, GaAs has a wide and direct band gap of 1.42eV. On the other hand, silicon has an indirect band gap of 1.1eV. So, GaAs is a very valuable material for switches, high speed operating as well as optoelectronic devices [12]. The value of the energy gap for GaAs at room temperature is 1.42 eV, but it is assumed to be 1.53 eV at 0 K [13]. Fig. 3 shows the band structure of gallium arsenide.

Table 1 Properties of GaAs material [4]

Type	Crystal Structure	Lattice Constant at 300K (Å)	Dielectric constant
Group III-V Compound	Zinc blende	5.6533	13.1

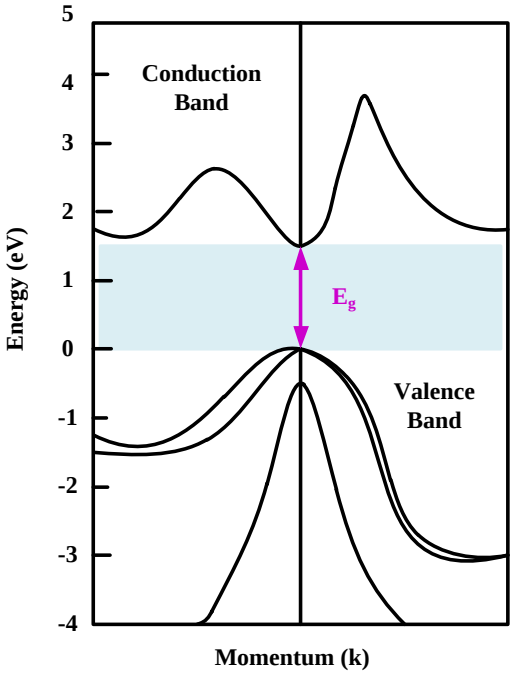

Fig. 3 Band structure of GaAs [1]

3. Temperature Dependence of Band-Gap Energy

The band-gap energy was examined by the temperature dependence parameters. The energy level expressed in terms of temperature ranges for the material was surveyed by Varshni in 1967. The following formula expresses the energy band-gap depending on the temperature and Varshni's parameters of the material [5]:

$$E_g = E_g(0K) - \frac{\alpha T^2}{T+\beta} \quad (1)$$

where E_g is energy band gap of the material, T is temperature value (K), and α and β are fitting (otherwise called Varshni) parameters.

The band gap energy as a function of temperature for several semiconductor materials is along with the values for fitting parameters. Assume that the change in band-gap energy is the dominant factor in defining the voltage of the device depending on the temperature values. The temperature reliance of the forward voltage follows directly from the temperature dependence of the band gap energy. Table 2 shows the Varshni parameter values for gallium arsenide.

Table 2 Parameters for Materials [14]

Materials	E_g (0K)	α (10^{-4} eV/K)	β (K)
Si	1.170	4.73	636
Ge	0.744	4.77	235
GaAs	1.519	5.41	204

4. Implementation Procedure for Energy Band Diagram

For the research of energy band, donor concentration (N_d) is considered as $2x10^{17}$ cm^{-3}. The conduction band edges (E_{cN}-F_N) is required to consider at room temperature (T=300 K). The value of charge, q is 1.6 x 10^{-19} C. The implementation for the energy band result is in the following step by step procedure.

The Boltzmann's constant is:

$$k_B = 8.6175\times10^{-5}\,eV/K$$

The electron effective mass and that of holes for GaAs are:

$$m_e^* = 0.0665m_0$$

$$m_h^* = 0.50m_0$$

The dielectric constant for GaAs is:

$$\varepsilon_n = 13.1\varepsilon_0$$

The vacuum permittivity is:

$$\varepsilon_0 = 8.854\times10^{-14}\,As/(Vcm)$$

The band-gap energy, E_{gn} for gallium arsenide semiconductor is:

$$E_{gn} = 1.424eV$$

The concentration of the conduction band is considered as:

$$N_c = 2.51\times10^{19}\left[\frac{m_e^*}{m_0}\frac{T}{300}\right]^{3/2} cm^{-3} \quad (2)$$

The semiconductor band edges are:

$$E_{cn} - F_n = -k_B T \ln\frac{N_d}{N_c} \quad (3)$$

$$V_{on} - V_n = \frac{qN_d}{2\varepsilon_n}x_n^2 \quad (4)$$

The contact potential is as follows:

$$V_0 = \frac{E_{gn} + \Delta E_V - (F_p - E_{vp}) - (E_{cN} - F_N)}{q} \quad (5)$$

Where E_{gn} is energy band-gap of n-type (eV), ΔE_v is band edge discontinuities (eV), F_p is Fermi level of p-type (eV), E_{vp} is valence band edge of p-type material (eV), E_{cN} is conduction band level of N-doped material (eV), F_N is Fermi level of N-doped portion (eV) and q is electric charge (C).

The depletion region width for semiconductor is:

$$x_n = \left[\frac{2\varepsilon_n V_0}{qN_dN_A\left(N_A + \frac{\varepsilon_p}{\varepsilon_N}N_d\right)}\right]^{1/2} N_A \quad (6)$$

Where N_A is acceptor concentration (cm^{-3}), N_d is donor concentration (cm^{-3}), ε_p is dielectric constant for p-type and ε_N is

dielectric constant of N-doped material with wider band-gap than n-doped material.

5. Simulation Results

The section of simulation results includes three portions: current-voltage characteristic of the device, temperature dependence of energy using Varshni formula and band diagram for donor concentration of $2x10^{17}$ cm^{-3}. Fig. 4 illustrates the current-voltage characteristics of the device. It can be noted that the current condition consists of three portions. They are active region, saturated region and cut-off region. The gate voltages are 4V, 6V and 8V, as observed in Fig. 4.

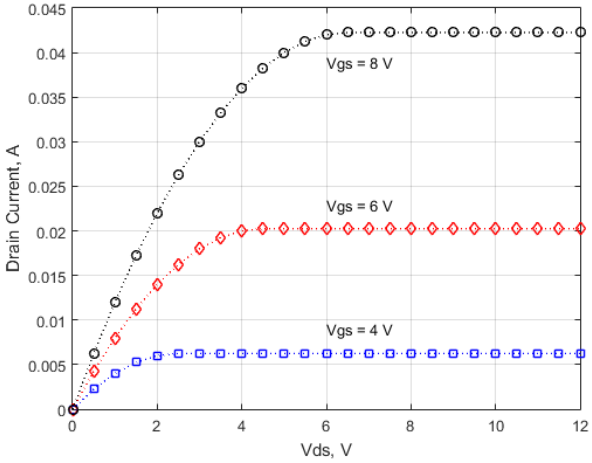

Fig. 4 I-V characteristics of a MOSFET

Fig. 5 shows the temperature variation of band-gap energy for gallium arsenide, silicon and germanium. Among the three types of materials, gallium arsenide has the highest energy level depending on temperature.

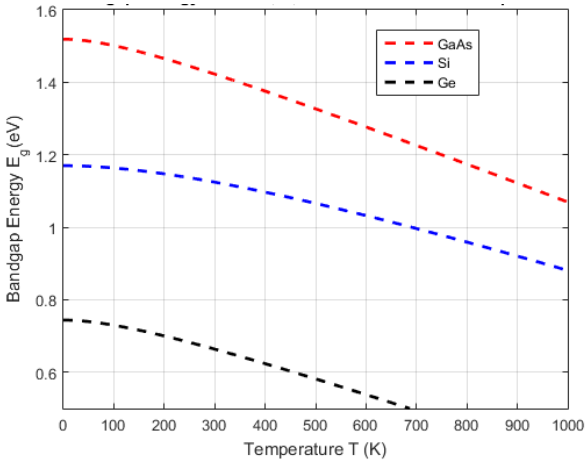

Fig. 5 Band-gap energy GaAs, Si and Ge expressed in terms of temperature

Fig. 6 shows an energy band structure to design the MOSFET. The resultant figure is simulated by using mathematical equations and MATLAB programming language. As can be observed from Fig. 6, the green and the blue lines are for conduction and valence bands of energy diagram, respectively. To complete the transistor modeling, the band structure is considered as metal-semiconductor-metal junctions of the device.

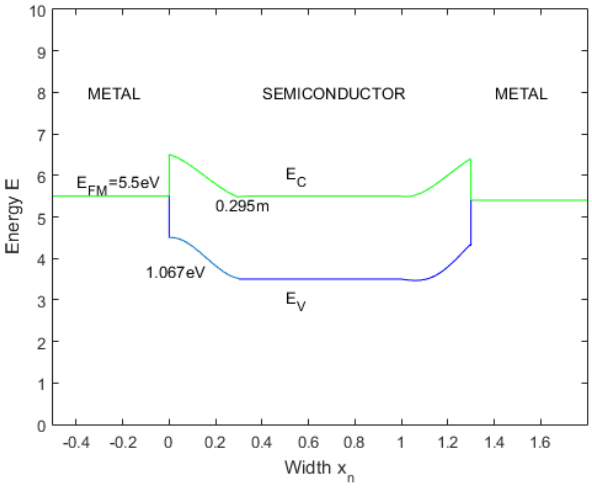

Fig. 6 Band diagram for specific donor concentration, N_d = 2 x 10^{17} cm^{-3}

6. Conclusion

In this paper, the band diagram results are seen to be investigated carefully. Also, the current condition flowing through the device was analyzed by using software simulation method. It was found that the resultant characteristics produce the properties for MOSFET development. Further discussion has been found that other parameters for MOSFET modeling can be tested again.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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